DOT/FAA/TC-12/41

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

The Effect of Surface Treatment on the Degradation of Composite Adhesives

August 2014

Final Report

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-12/41		

4. Title and Subtitle	5. Report Date
THE EFFECT OF SURFACE TREATMENT ON THE DEGRADATION OF COMPOSITE ADHESIVES	August 2014
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
[1]Lloyd V. Smith, [1]Prasanthi Pothakamuri, and [2]Peter J. VanVoast	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
[1]Washington State University 173 Bohler Pullman, WA 99164 [2]The Boeing Company P.O. Box 3707 Seattle, Washington 98124	
	11. Contract or Grant No. 04-C-AM-WSU
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Northwest Mountain Region – Transport Airplane Directorate 1601 Lind Avenue, SW Renton, WA 98057	Final Report
	14. Sponsoring Agency Code AIR-100

15. Supplementary Notes

The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division Technical Monitor was David Westlund.

16. Abstract

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17. Key Words	18. Distribution Statement
Composites, Adhesive, Bonding, Surface preparation, Lap shear, Strain energy release rate, Double cantilever beam, Grit-blasting	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	34	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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LIST OF SYMBOLS AND ACRONYMS

G_{IC}	Strain energy release rate
T_g	Glass transition temperature
CILS	Compression interlaminar shear
DCB	Double cantilever beam
FEP	Fluorinated ethylene propylene
IPS	In-plane shear
SRB	Super Release Blue
TWLS	Thick wide area lap shear

EXECUTIVE SUMMARY

To ensure the commercial fleet longevity, the long-term durability of a primary aircraft structure must be understood. The degradation of metals and their attachments (mechanical and adhesive) has been rigorously studied over the years. The introduction of composite materials in aerospace applications has presented challenges because methodologies that have been used successfully with metals do not consistently produce reliable results with new materials. This study considered the effect of surface treatments on composite adherends and accelerated test methods that may be used to compare their long-term degradation.

BMS 8-276 Form 3 laminates were prepared for bonding using polyester (Precision Fabrics Group, Inc. 60001), nylon (Precision Fabrics Group, Inc. 52006), siloxane-coated polyester (Super Release Blue (SRB)), and nylon peel ply. The effect of secondary abrasion was considered by sanding (220 grit) and grit blasting (80 and 220 grit). All specimens were bonded at 350°F with AF555 (3M™) that was formulated to be moisture resistant.

Using thick-adherend, wide-area lap shear specimens, the AF555 adhesive was resistant to prebond moisture content. However, for both the low-cost and classic material forms, the composite adherends tended to fail by interlaminar shear as the moisture content increased.

Of the surfaces prepared from the three peel plies, polyester provided superior shear strength and fracture toughness with cohesive and interlaminar failure modes. Secondary abrasive operations did little to improve adhesion beyond the polyester peel ply and, in some cases, lowered the bond strength. Sanded surfaces had slightly higher strain energy release rates (G_{IC}) than peel ply, while grit-blasted surfaces had significantly lower G_{IC}. The grit-blasting operation caused surface damage that may have contributed to reduction in strength.

Combining stress, temperature, and moisture accelerated degradation beyond the effect of these components individually. Temperature accelerated moisture diffusion. The residual shear strength decreased with creep stress. Crack growth in double cantilever beam specimens was also accelerated using a fluctuating load while immersed in water.

1. INTRODUCTION.

The environmental degradation of a material involves a relatively low-rate chemical reaction. The reaction rate is usually dependent on temperature, solvent concentration, and material stress. In some cases, the simultaneous application of these parameters can increase the reaction rate beyond the sum of their separate effects; however, the ability of these parameters to accelerate degradation is limited. For example, increasing the temperature or solvent concentration to extreme levels can initiate reactions that would not occur, even at long durations, under normal service exposure conditions. A similar limitation involves high levels of stress that can induce failure without having an appreciable effect on the reaction rate.

Another method of accelerating degradation involves the application of an oscillating load to a material immersed in a hostile environment. The oscillating load can induce distributed damage that can increase the surface area and diffusion rate for the solvent. The distributed damage will also produce localized regions of high stress to further accelerate the degradative process.

One difficulty when combining load, temperature, and environment involves the practical problem of supplying equipment in sufficient quantities to perform a statistically significant test within an accelerated time frame. The compact pneumatic creep frames, developed for the Environmental Exposure Facility at Washington State University, can address this problem. Their operation is intrinsically in load control. While their frequency response is relatively low, the exposure duration needed for environmental degradation allows for the accumulation of a large number of cycles (potentially, over 3 million in 1000 hours or 42 days).

Of the numerous fluids that may have the potential of long-term exposure to a primary structure in a commercial aircraft, the hot, wet environment was the most aggressive. Hot, wet environments are often achieved in the laboratory using humidity controlled ovens. The number and type of specimen proposed for this study made this form of environmental chamber impractical. Instead, a hot, wet environment of 140°F was achieved by immersing the specimen in a heated water bath.

2. BACKGROUND.

2.1 FAILURE MODES.

As shown in figure 1, an adhesively bonded composite joint typically fails in one of three modes. Good adhesion is typically associated with adherend or cohesive failure. The strength of these bonds is a function of the adherend and adhesive strength, respectively. Adhesion failure is due to poor bonding. The strength of the bond is a function of the chemical compatibility between the adherend and adhesive, processing parameters, and impurities. Surface preparation, which is the primary area studied for this report, can have a significant impact on the bond strength.

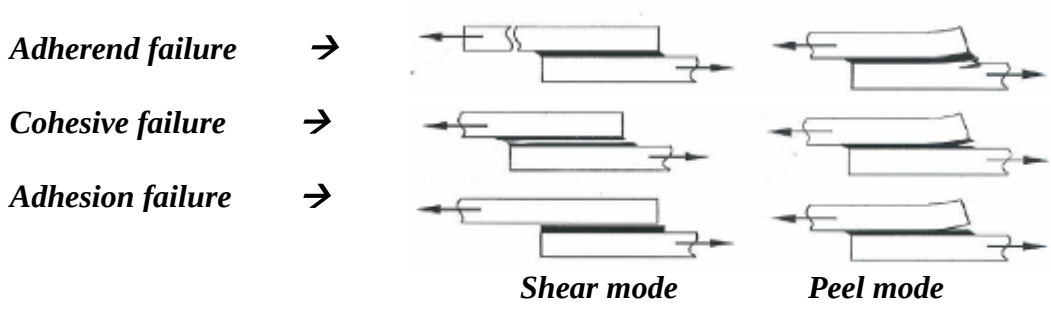


Figure 1. Failure Modes of an Adhesively Bonded Composite Joint [1]

2.2 DIFFUSION.

The kinetics of fluid absorption in polymers has been studied for some time, beginning with Fick (1855). Polymers tend to absorb moisture and gain weight in wet environments and desorb moisture and lose weight in dry environments. The magnitude and rate of diffusion depended on the polymer's stress state, the solvent's concentration, and the temperature. A one-dimensional Fickian curve is represented by the line LF in figure 2, where a normalized weight change is plotted as a function of the square root of time. Non-Fickian diffusion was also observed. In some cases, the response was elastic (curves A and B) while, in other cases, the response was associated with degradation (curves C and D). The Pseudo-Fickian response of curve A corresponds to continuous gradual increase in weight never attaining equilibrium. Curve B represents a two-stage diffusion behavior, which can be due to a phase change in the polymer. Curve C is usually accompanied by large deformation, damage growth, material break down, or mechanical failure. Curve D indicates material leaching into the solvent with irreversible chemical or physical breakdown.

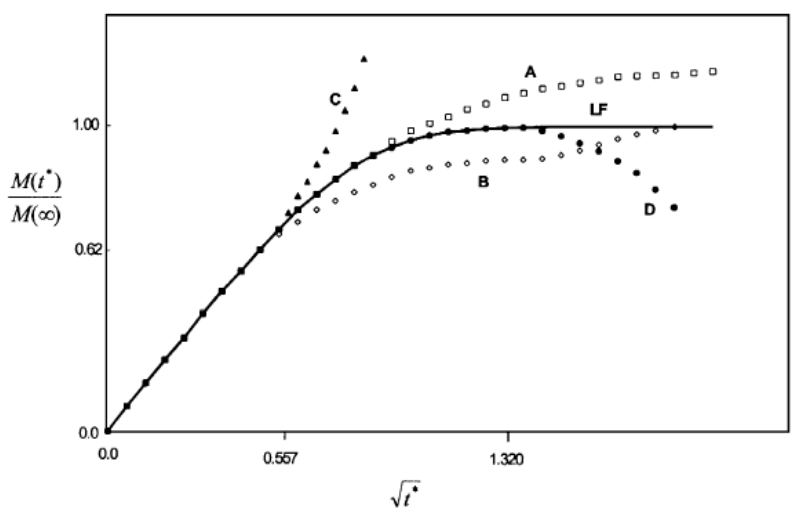


Figure 2. Normalized Weight Change Representing Fickian and Non-Fickian Polymeric Diffusion [2]

Observing the trends depicted in figure 2 are challenging due to the long time scales and large thickness dependence associated with diffusion. In one study, weight gain observations of graphite/epoxy and glass/epoxy composites followed a benign curve B for 3 years, and beyond that, the data shifted towards curves C and D [2].

Moisture tends to lower the glass transition temperature (T_g) of polymers and the strength of the fiber/matrix interface in composites. Glass and carbon fibers do not absorb moisture, although they can degrade in aggressive environments. For composites exposed to hot, wet conditions, the most significant loss occurs in the compressive strength [3]. The effect of moisture at the fiber/matrix interface is two-fold. First, the moisture can directly reduce the chemical-bonding strength at the interface. Second, the matrix swelling that accompanies moisture absorption can minimize beneficial residual cure stresses [4]. The interfacial shear strength is due to mechanical, as well as chemical, interaction at the interface. The relaxation of residual compressive stresses at the interface reduces the interfacial shear strength [5]. Generally, the tensile strength of unidirectional composites is unaffected by moisture absorption, while reductions in the compressive strength of unidirectional composites range from 10% to 50% [5].

The previous paragraphs discuss the effects of diffusion on cured materials. Moisture in adherends prior to bonding can interfere with surface wetting, chemical reaction during cure, and induce excessive voids [6]. These adverse effects can be readily mitigated through appropriate drying of the constituents; however, thorough drying can require days and rarely occurs in practice. Therefore, it is helpful to understand the effect of prebond moisture on bond integrity and to investigate the options that reduce adverse effects.

2.3 COMBINED EFFECTS.

Numerous studies considered the effects of environment, temperature, or mechanical stress on polymers individually; however, their combined contribution has received less attention though the work that was done appeared to show an effect. For instance, diffusion alone did little to the tensile strength, while moisture coupled with load and temperature substantially lowered the tensile strength of an e-glass/vinyl-ester composite [7].

Since diffusion and swelling precede chemical reaction and degradation, the effects of moisture can change with exposure duration. At short durations (less than 1000 hours), the tensile strength of an e-glass/epoxy system under immersed creep increased [8]. The tensile strength decreased at long durations (more than 3000 hours) and at short durations when heat was applied (65°C). In this case, the strength reduction was due to a degrading fiber-matrix interface that accelerated with stress and elevated temperature.

In comparison to the e-glass systems, the tensile strength of carbon fiber reinforced polymers was less sensitive to immersed creep. This was apparently due to a more robust fiber-matrix interface. Matrix-dominated loading that involved transverse and shear stresses with moisture and elevated temperature caused a reduction of their respective strengths [9].

A classic example of the significance of combined stress and environment was observed with nylon fibers in NO_x [10]. Creep stress alone had a minimal effect on the tensile strength of fiber bundles, however, in a NO_x environment, stress was observed to accelerate degradation substantially. The effect of combined environments was persistent with bare fibers and fiber bundles embedded in a polymer matrix.

Aloha Flight 243 is another example of the significance of combined environments on adhesion [11]. While surface preparation and joint design were significant factors in the failure, the disbond leading to failure occurred under a combined environment of moisture and load.

2.4 BOND DURABILITY.

Adhesive bonds are often characterized by their lap shear strength, peel resistance, or residual strength after controlled environmental exposure. Results of this work show increased degradation when load and environment are combined [12]. Unfortunately, the cohesive laboratory failure modes often do not match adhesive service failure modes, making the relevance of these results to the effects from service exposure unclear.

The wedge crack test method was developed to provide an improved comparison of bonded aluminum joints (ASTM D3762). This method involved forcing a wedge into a bonded joint with a precrack [13]. Crack growth often occured at the primer surface without plastic deformation of the adherends in less than 24 hours. The failure modes from this specimen also tended to agree with service exposure. This method was particularly helpful in accelerating crack propagation of aluminum adherends from oxidizing primer surfaces in humid environments.

The durability of adhesively bonded composite joints was also considered [14 and 15]. Surface preparation and contamination played an important roll in bond integrity. Surface quality was strongly influenced by the peel ply used in processing. In particular, peel-ply containing silicone agents significantly reduced the strain energy release rates (G_{IC}). Grit blasting tended to increase the G_{IC}, but it did not change the adhesive failure mode of surfaces containing silicone.

This section reviews some of the progress that was made in evaluating metallic and composite adhesively bonded joints. Although the results of this work have contributed to our understanding of bonded joints, the need for additional work is apparent. The effect of combining service load and environment is not well understood and a relatively small amount of research has been performed. A method of measuring environmental effects on a reduced time scale is also needed.

Manufacturers of commercial composite aircraft are using peel ply and grit-blasting surface preparation techniques to bond primary structure. The durability of the adhesive bonds is affected by the adherend surface quality, pre- and post-bond moisture content, and service loads. The following section discusses how surface preparation affects the integrity of adhesive bonds and investigates test methods that may be used to accelerate degradation.

3. RESULTS.

3.1 MATERIALS AND PROCESSES.

The carbon/epoxy adherends used for adhesive bonding were made from Toray T800/3900-2 (BMS 8-276 Form 1) or T800/3900-2B (BMS 8-276 Form 3). The materials were referred to as classic (Form 1) and low cost (Form 3). Prepreg laminates were vacuum bagged with mold release on the tool side and a peel ply on the top surface. The panels were cured using a recipe provided by Boeing [16]. Vacuum was applied (22 in.-Hg) and autoclave pressure was raised to 85 psi. The temperature was then raised at 3°F (1.7ºC) per minute to 355ºF (180ºC) for 120 to 180 minutes. After the soak, the part was cooled at 5ºF (3ºC) per minute to 140°F (60ºC) after which the pressure was released and the part was removed from the autoclave.

The composite panels were cured using a polyester (Precision Fabrics 60001), nylon (Precision Fabrics 52006), or siloxane-coated polyester (Super Release Blue (SRB)) peel ply. The textures of the three fabrics were fine, medium, and coarse, respectively.

3.2 TEST METHODS.

The composite panels were bonded using 3M™ AF555 (BMS 5-160 Grade 5), which was provided in a 0.01-in.-thick, 0.05-lb/ft^2 areal weight film adhesive form. The peel ply was removed from the part within 20 minutes of bonding, then the adhesive was cured at 350°F following the prepreg recipe.

Double cantilever beam (DCB) specimens were made from bonded adherends comprised of ten plies of unidirectional prepreg. A fluorinated ethylene propylene (FEP) separator film was used as a crack initiator. As shown in figure 3, the DCB specimens were 0.16 in. thick, 0.50 in. wide, 13 in. long, and had an initial crack length of 2 in.

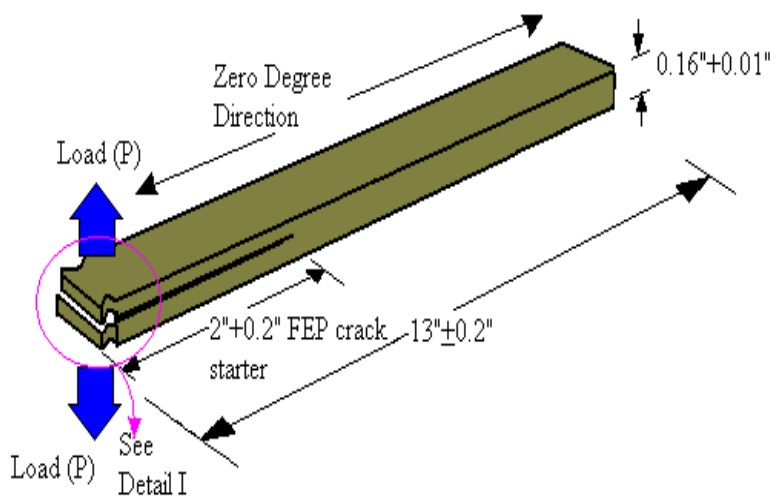


Figure 3. Double Cantilever Beam Specimen

Wedge crack specimens were made from bonded adherends comprised of ten plies of unidirectional prepreg. An FEP separator film was used as a crack initiator. The specimens were 0.16 in. thick, 6 in. long, 1 in. wide, and had an initial crack length of 2 in. As shown in figure 4, the wedge was 1 in. long made from a 0.125-in.-thick aluminum, which was inserted in the precrack, flush to the end of the specimen.

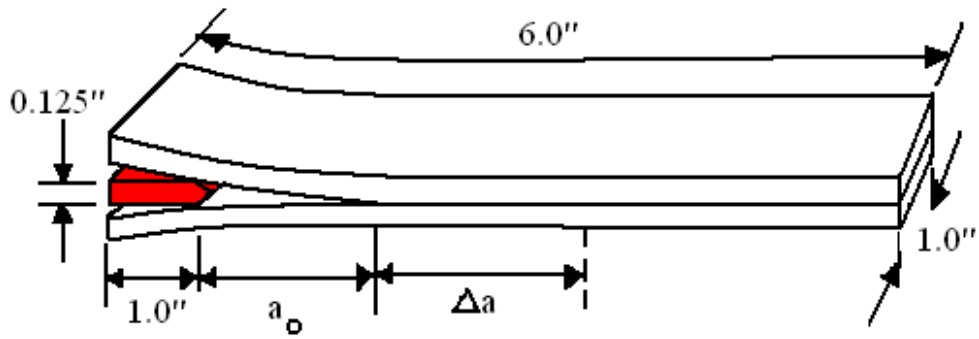


Figure 4. Wedge Crack Specimen

Thick wide area lap shear (TWLS) specimens were made from bonded adherends comprised of 20 unidirectional plies of prepreg, which were formed by bonding 7-in.-long by 1-in.-wide adherends. The shear region was formed by machining a 0.218-in.-wide slot through the adherend into the adhesive on either side of the specimen. As shown in figure 5, the slot ended 3.25 in. from each end of the specimen, leaving a 0.50-in.-long gage section.

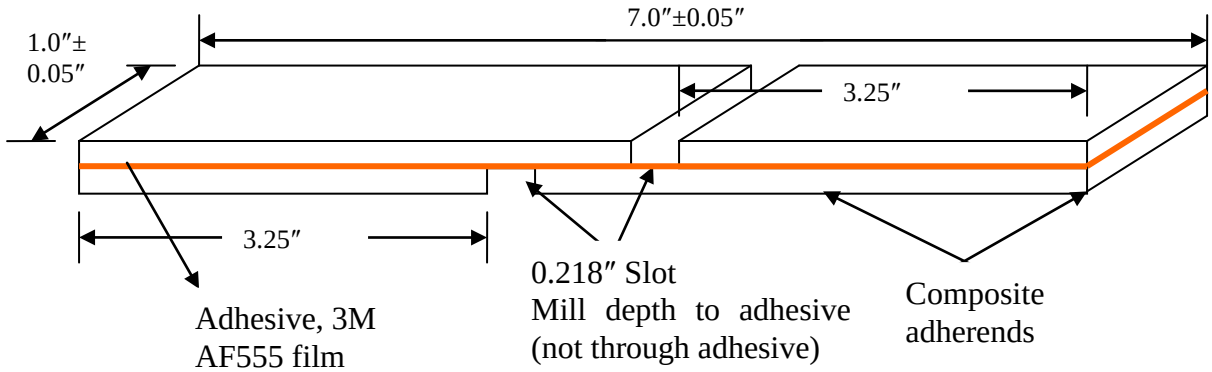


Figure 5. Thick Wide Area Lap Shear Specimen

Compression interlaminar shear (CILS) specimens were made from 24 plies of unidirectional prepreg (no adhesive). These specimens measured 3.18 in. long and 0.50 in. wide. The shear region was formed by machining a 0.10-in.-wide slot, 0.092 in. deep or half way through the thickness of the specimen. As shown in figure 6, the slot ended 1.465 in. from each end of the specimen, leaving a 0.25-in.-long gage section.

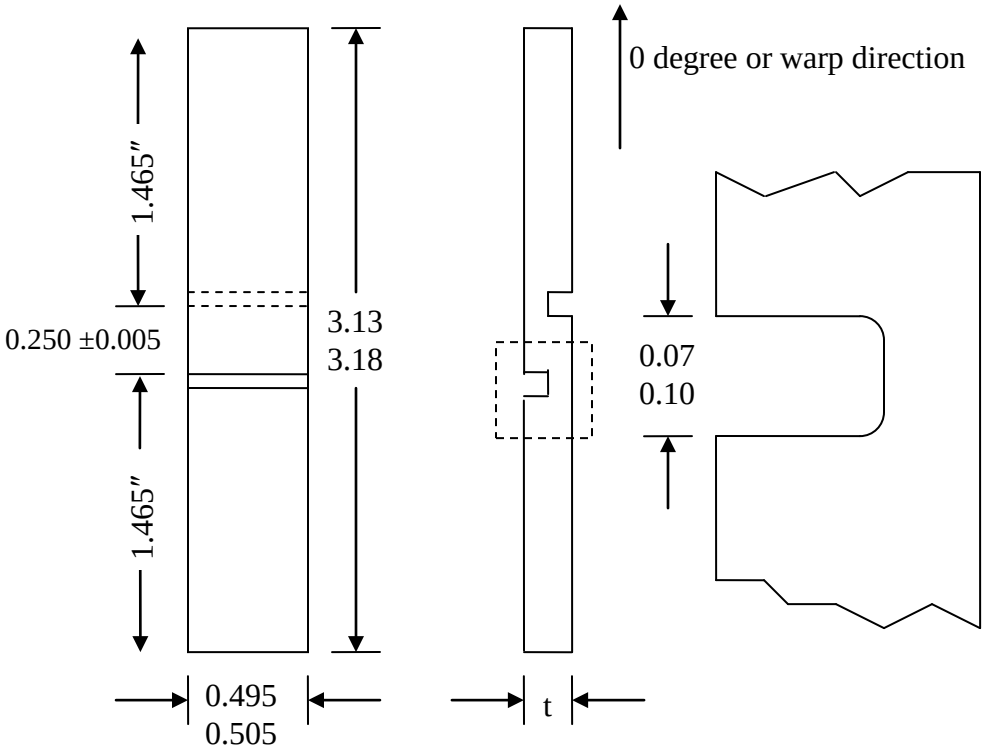


Figure 6. Compression Interlaminar Shear Specimen

In-plane shear (IPS) specimens were made from four plies of prepreg with a lay-up of $[\pm 45]_s$. As shown in figure 7, these specimens were 9 in. long, 0.50 in. wide, with 2-in.-long, tapered, glass/epoxy endtabs.

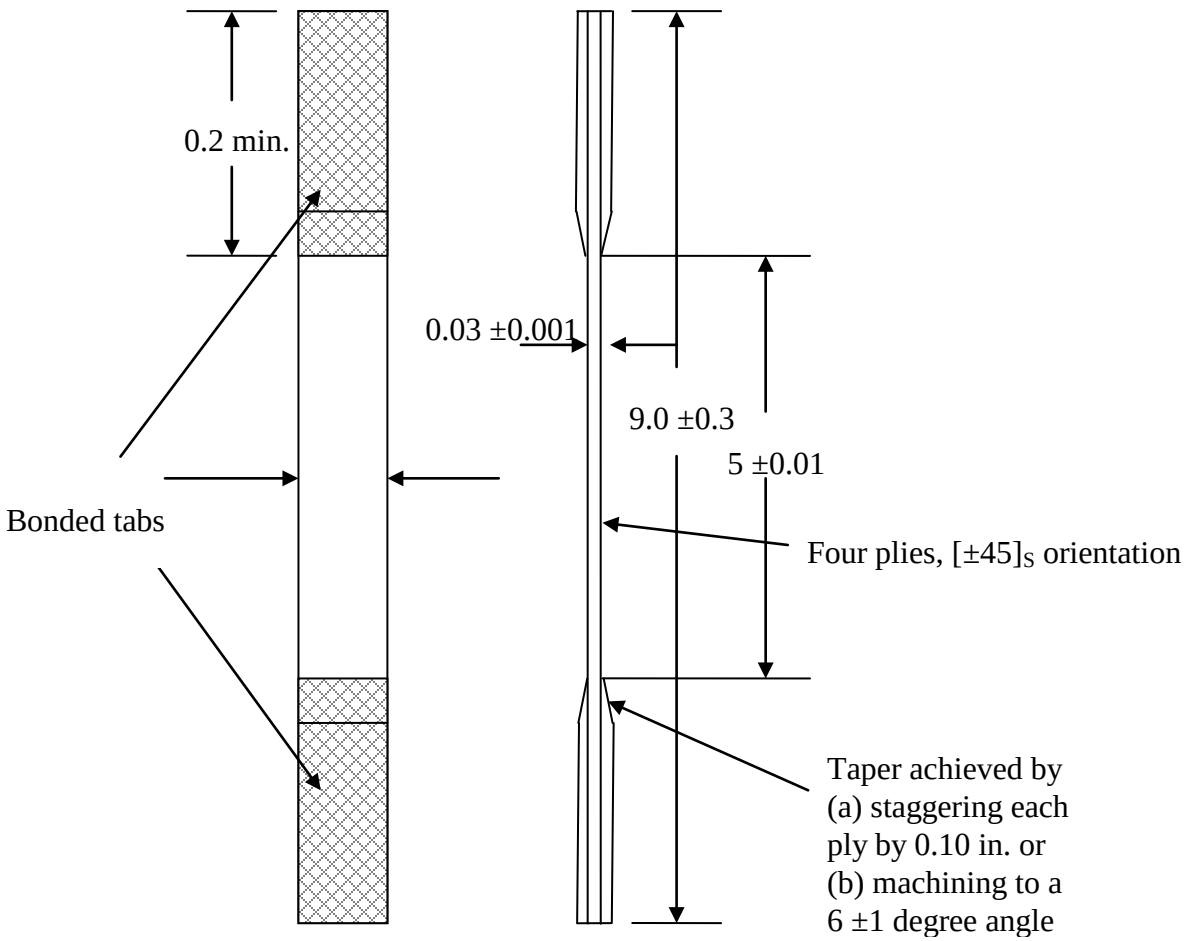


Figure 7. In-Plane Shear Specimen

3.3 EFFECT OF MOISTURE.

Adhesives and their adherends are typically dried before bonding operations are performed due to their sensitivity to the prebond moisture content [17-19]. The AF555 (3M) adhesive is formulated to be insensitive to the prebond moisture content. The goal of this portion of the study was to verify the bond quality and environmental durability in the presence of prebond moisture.

TWLS specimens were made from the low-cost form of the prepreg material using a polyester peel ply and bonded with dry and wet (1% moisture) adherends. The bonded specimens were immersed in 140ºF water for 1000 hours. The specimens were then given a creep load of either 2, 3, or 4 ksi for an additional 1000 hours while immersed in 140°F water. The residual shear strength of these specimens is presented in figure 8 and appears to be relatively insensitive to the prebond moisture content.

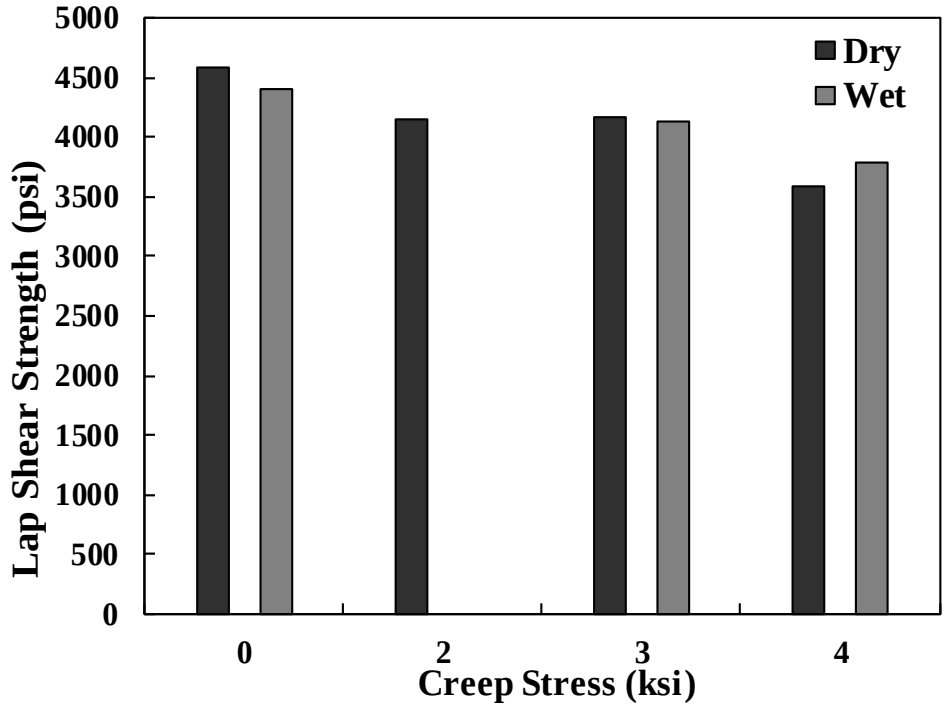


Figure 8. Residual Shear Strength of TWLS Specimens

Representative failure surfaces of the dry and wet specimens are presented in figures 9 and 10, respectively. While the surfaces appear consistent with adhesive failure, closer inspection shows evidence of adherend failure. The failure surfaces show bare fibers with no evidence of the texture of the peel ply. The prepreg used in this study used a thin film on its surface as a toughening agent. It was apparent that the disbond from the fibers originated in the toughened region.

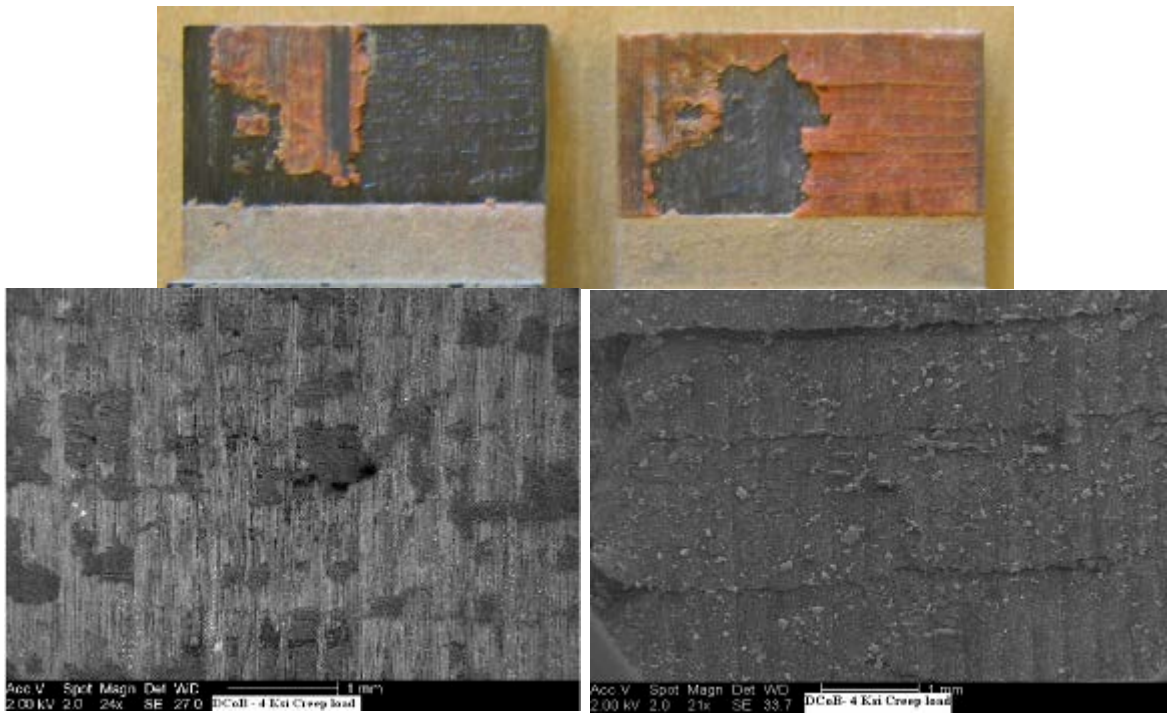


Figure 9. Fracture Surfaces of a Specimen Bonded With Dry Adherends Then Creep Loaded to 4 ksi While Immersed in 140°C Water

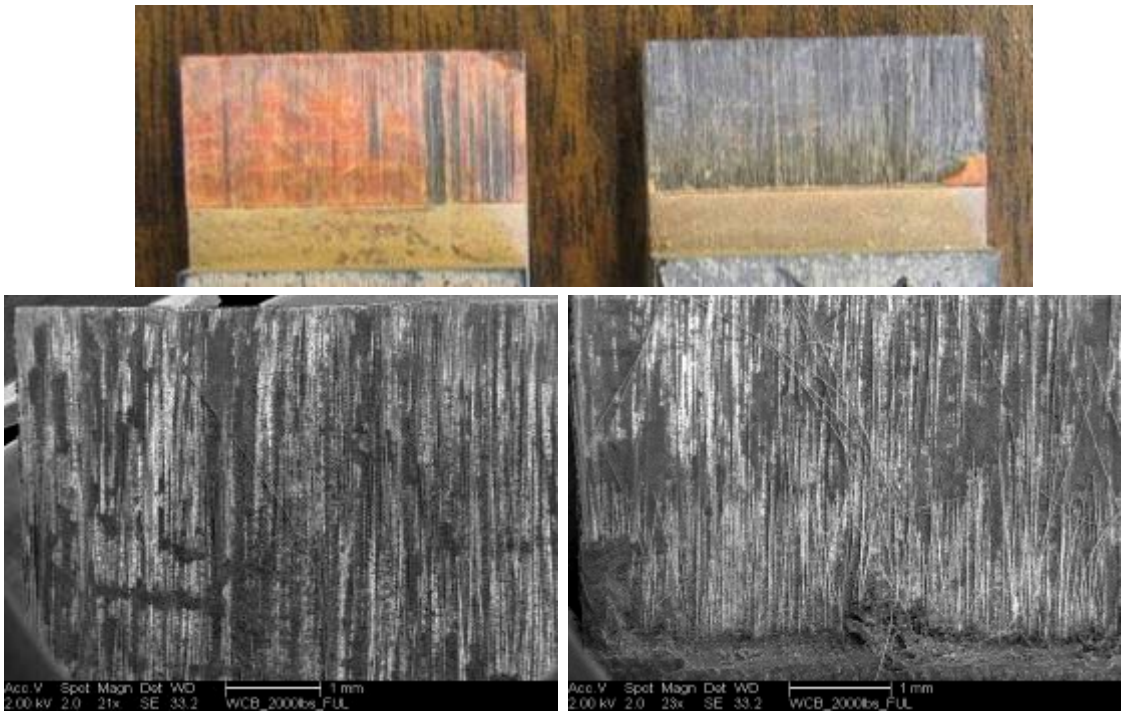


Figure 10. Fracture Surfaces of a Specimen Bonded With Wet Adherends Then Creep Loaded to 4 ksi While Immersed in 140°C Water

Figure 8 shows that the residual shear strength decreased with increasing creep load. Although this response was consistent with other adhesives [16 and 20-23], there was concern that the adherend failure mode may have been due to the low-cost material formulation. Therefore, the moisture study was included for the classic and low-cost material forms. CILS and IPS specimens were made from the two material forms to compare the matrix moisture resistance. The specimens were immersed in 160°F water and removed at regular intervals for mechanical testing. The CILS specimens were tested at 180°F, and the IPS specimens were tested at room temperature. As shown in figure 11, the average CILS strength decreased nearly 20% for both material forms. The average shear modulus from the IPS specimens is shown as a function of moisture content in figure 12. The modulus of both material forms decreased 10% at saturation. In both cases, the moisture dependence of the classic and low-cost material forms was nearly indistinguishable.

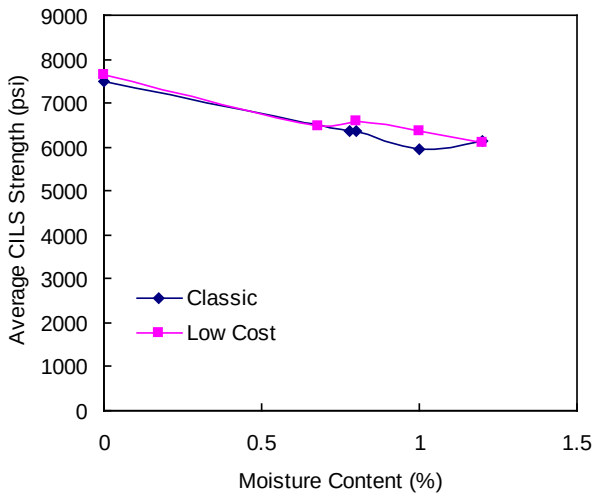


Figure 11. Average CILS Strength of the Classic and Low-Cost Material Forms

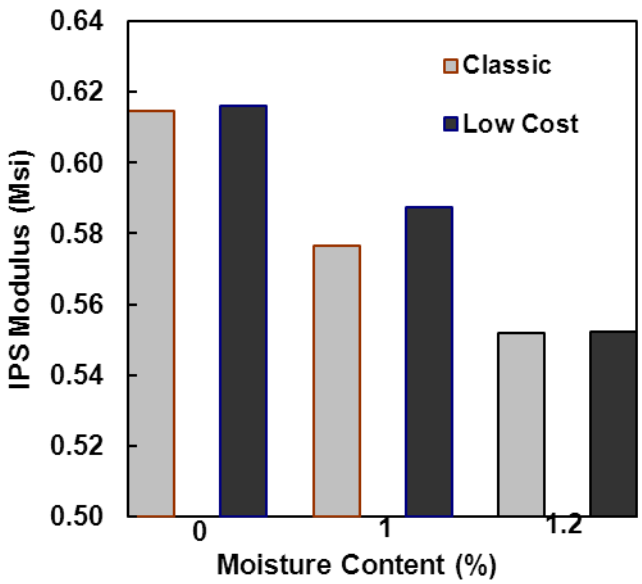


Figure 12. Modulus of IPS Specimens as a Function of Moisture Content

3.4 EFFECT OF PEEL PLY.

Peel ply is commonly used in autoclave processing of composite laminates. The surface created from peel ply removal can form an effective surface for adhesion. However, agents allowing easy removal of the peel ply can affect the integrity of subsequent adhesion. To consider these effects, panels were made using polyester, nylon, or SRB peel ply.

IPS and DCB specimens were immersed in 140° water to achieve saturation. The weight change of a traveler specimen was periodically recorded. The composite and adhesive had diffusion coefficients of 0.00106 and 0.0044 mm^2/hr, respectively, and a saturation level of 1.25% and 3.0%, respectively. The diffusion coefficient and saturation level of a bonded panel was 0.00138 mm^2/hr and 1.41%, respectively. A comparison of the measured weight change with Fick's law is shown in figure 13; the thicker specimens required 6000 hours to reach saturation.

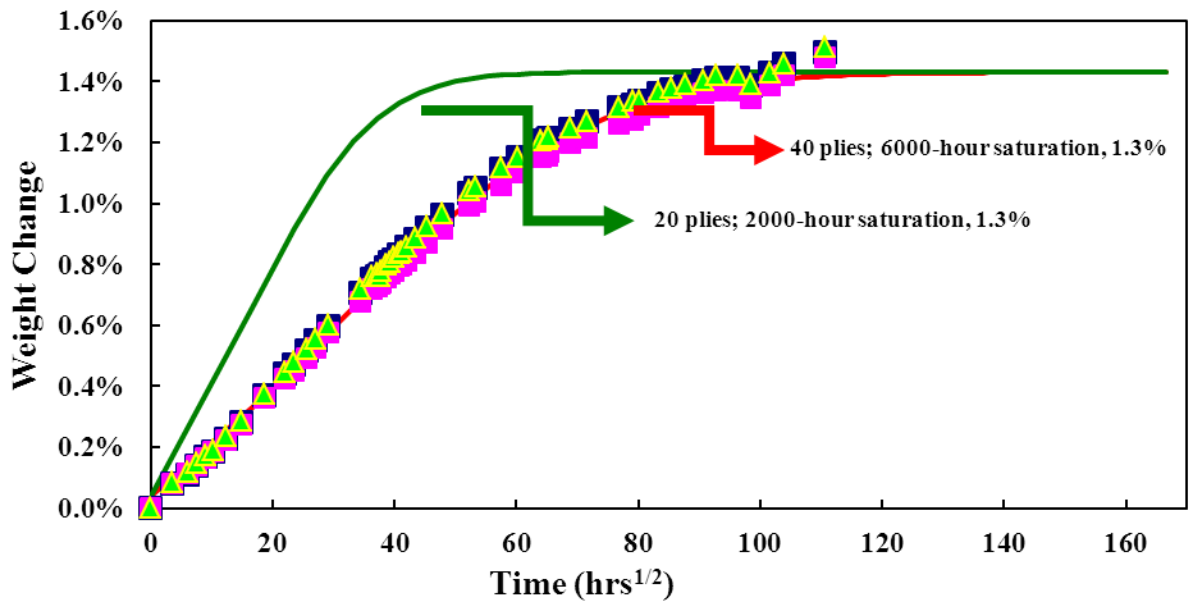


Figure 13. Weight Gain Data of 20- and 40-ply Bonded Specimens

As shown in figure 14, after reaching saturation, a baseline IPS strength was determined from five specimens for each peel ply surface. The effect of peel ply on the TWLS strength was relatively large, where the polyester peel ply was more than twice as strong as the SRB peel ply. Images of representative failure surfaces are shown in figure 15. The SRB and nylon specimens were dominated by adhesive failure, while the polyester specimens had a mixed cohesive and adherend failure. The poor adhesion found with SRB was apparently due to the silicone used as a release agent in this material, while the nylon peel ply was observed to leave significant amounts of nitrogen and amide groups on the surface [24].

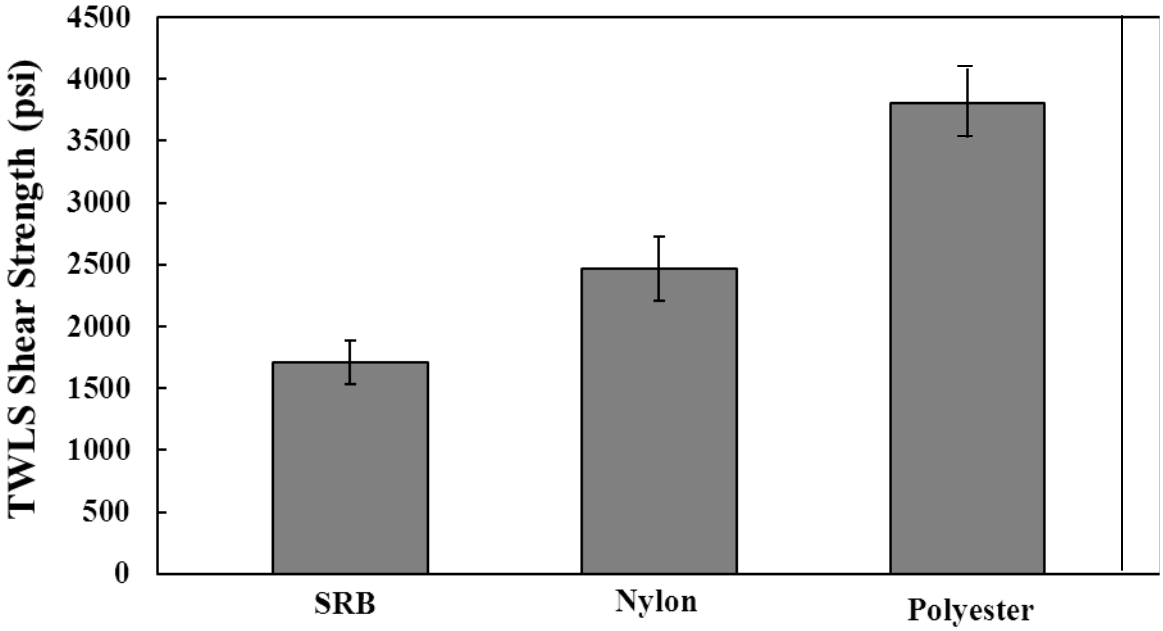
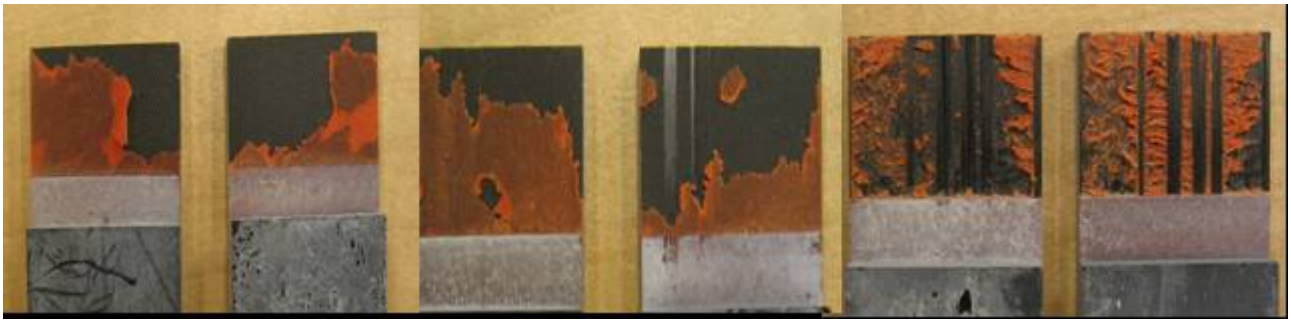
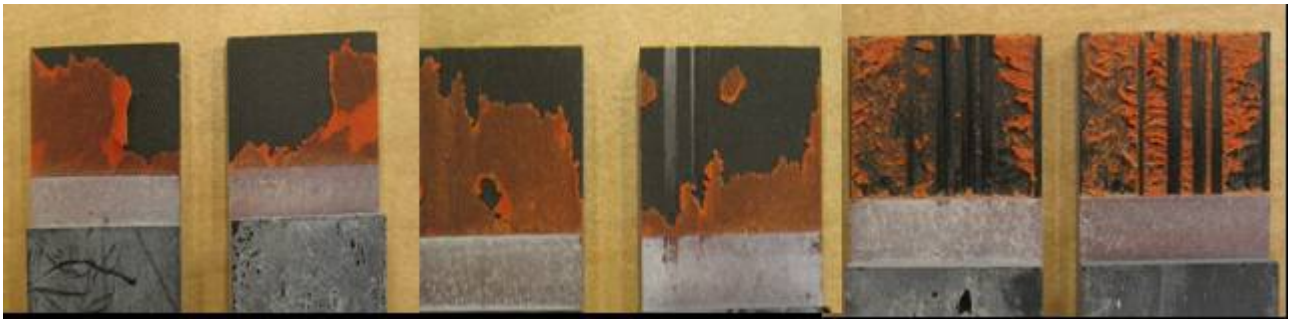


Figure 14. Baseline Shear Strength of Saturated TWLS Specimens



SRB	Nylon	Polyester
100% adhesion	100% adhesion	50% adherend, 50% cohesive



SRB	Nylon	Polyester
100% adhesion	100% adhesion	50% adherend, 50% cohesive

Figure 15. Representative Failure Surfaces of the Baseline TWLS Specimens

Ten TWLS specimens from each peel ply were given a creep load of 80% of their respective baseline shear strength while immersed in 140°F water. The average creep rupture time of each peel ply is shown in figure 16. The results suggest that improved adhesion afforded by some peel ply materials also results in greater environmental durability. Representative failure surfaces of the creep rupture specimens are shown in figure 17. The failure modes are comparable to the baseline TWLS results, while the polyester specimens had slightly more adherend failure.

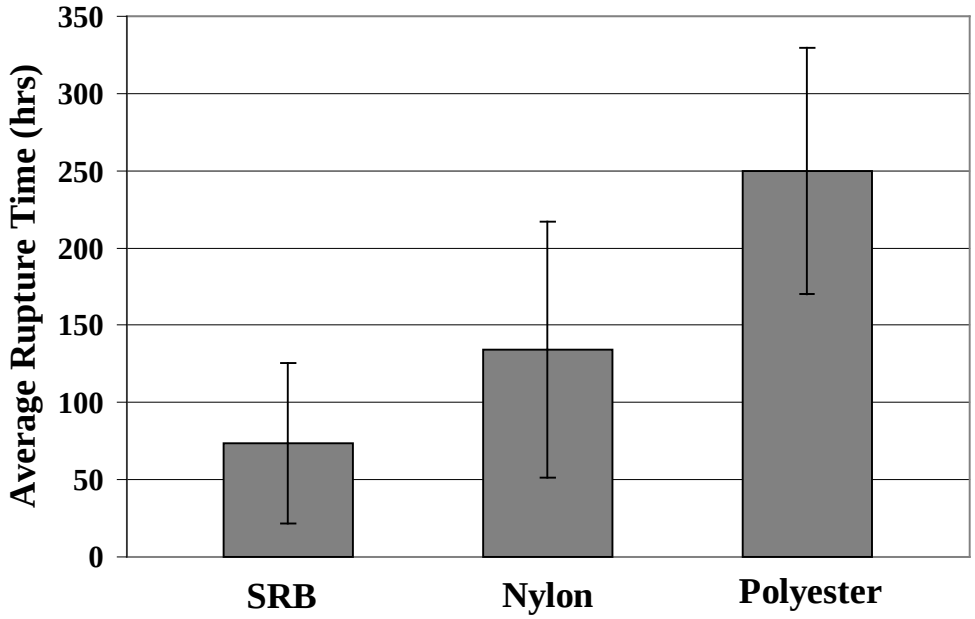


Figure 16. Average Creep Rupture Time as a Function of Surface Peel Ply

SRB
100% adhesion

Nylon
100% adhesion

Polyester
70% adherend, 30% cohesive

Figure 17. Representative Failure Surfaces of Creep Rupture TWLS Specimens

Figure 18 shows the comparison between the critical G_{IC} of five DCB specimens from each peel ply exposed to 140°F water for 6000 hours. Representative images of their failure surfaces are shown in figure 19. The effect of peel ply on the G_{IC} and the failure mode of the DCB specimens are comparable to the TWLS results shown above. However, the effect of peel ply on the G_{IC} was much greater than the shear strength.

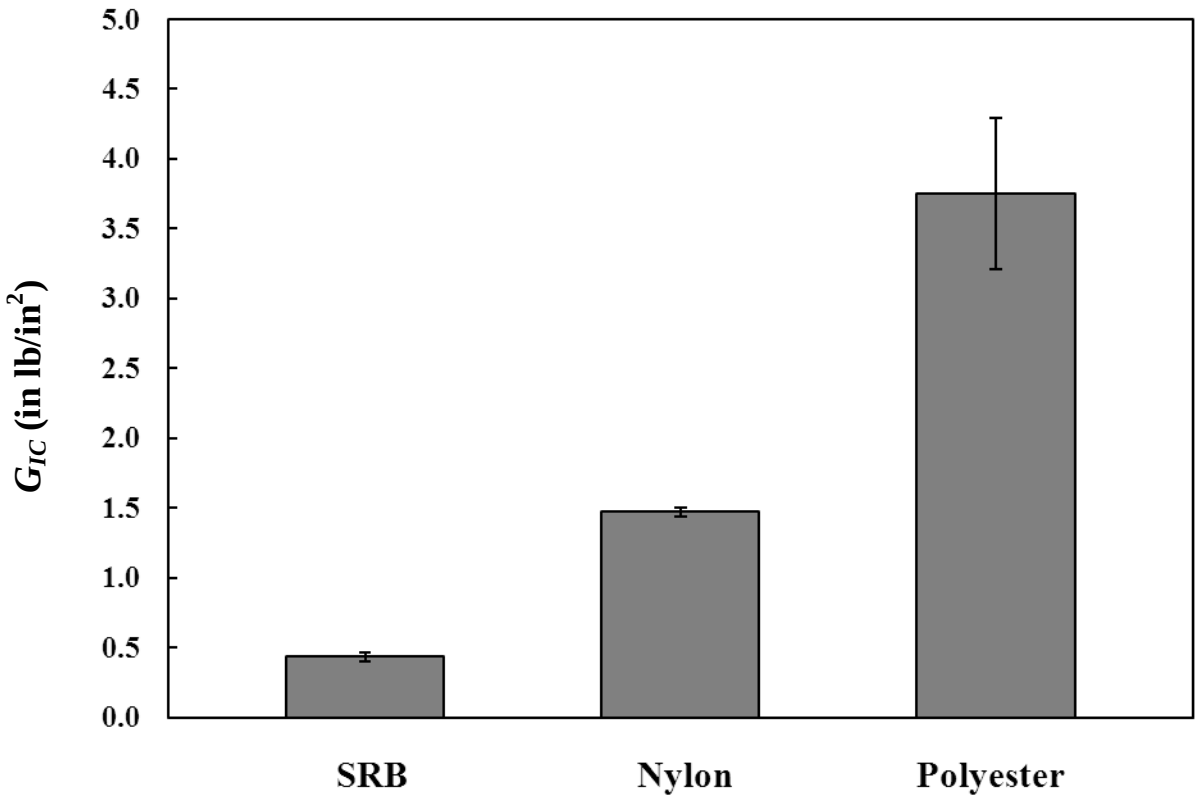
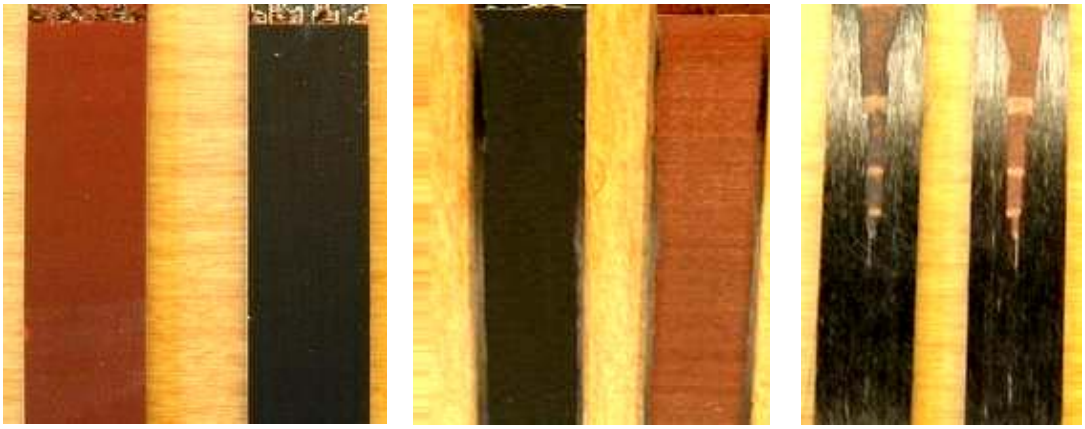


Figure 18. Critical Mode I G_{IC} of DCB Specimen as a Function of Peel Ply



SRB	**Nylon**	**Polyester**
100% adhesion	90% adhesion, 10% adherend	100% adherend

Figure 19. Failure Modes of DCB Specimen Tested After Immersed in Water for 6000 Hours

The wedge crack specimen has been relatively successful when testing studying adhesives and surface preparations for bonded aluminum structure [12]; however, its application to composite bonded structures has had mixed results. The following considers the effect of adherend stiffness on the crack growth of composite wedge crack specimens. The adherend bending stiffness of the standard aluminum wedge crack specimen is 1571 lb-in^2. Composite wedge crack specimens

were made with 8-, 10-, and 12-ply adherends. For comparison the 8-, 10-, and 12-ply adherends had a bending stiffness of 365, 696, and 1202 lb-in^2, respectively. Panels were prepared using the SRB, nylon, and polyester peel ply.

After the wedge was inserted and the initial crack length was measured, five replicates of each peel ply and adherend combination were immersed in 140°F water. The initial crack length for each adherend and peel ply combination is shown in figure 20. The effect of the initial crack length on the peel ply of the wedge crack specimens is similar to that found for the TWLS and DCB specimens, although the dependence is substantially lower. The effect of adherend bending stiffness is not consistent with the initial crack length. The relatively small sensitivity of the wedge crack specimen suggests the effects of adherend bending stiffness may be smaller than adhesion process variation.

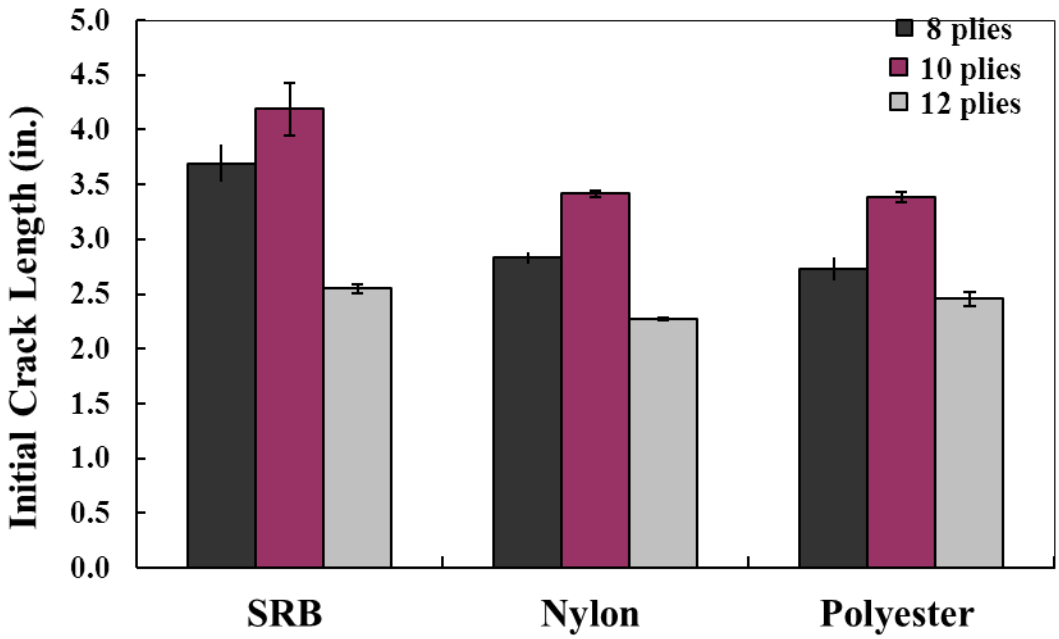


Figure 20. Initial Crack Length of Composite Wedge Crack Specimens

Wedge-crack growth of the composite specimens after 24-hour immersion in 140°F water is compared for each peel ply in figure 21. The sensitivity of the specimen decreased with increased adherend stiffness, and the crack growth of the 12-ply adherends was nearly constant. Although crack growth is more apparent with the lower-stiffness adherends, the results are not entirely consistent with thickness. The processing-induced variation observed in the initial crack length appeared to also have influenced the 24-hour crack growth. A variation of the wedge crack method involving a constant load, as opposed to a constant displacement, will be discussed in the next section.

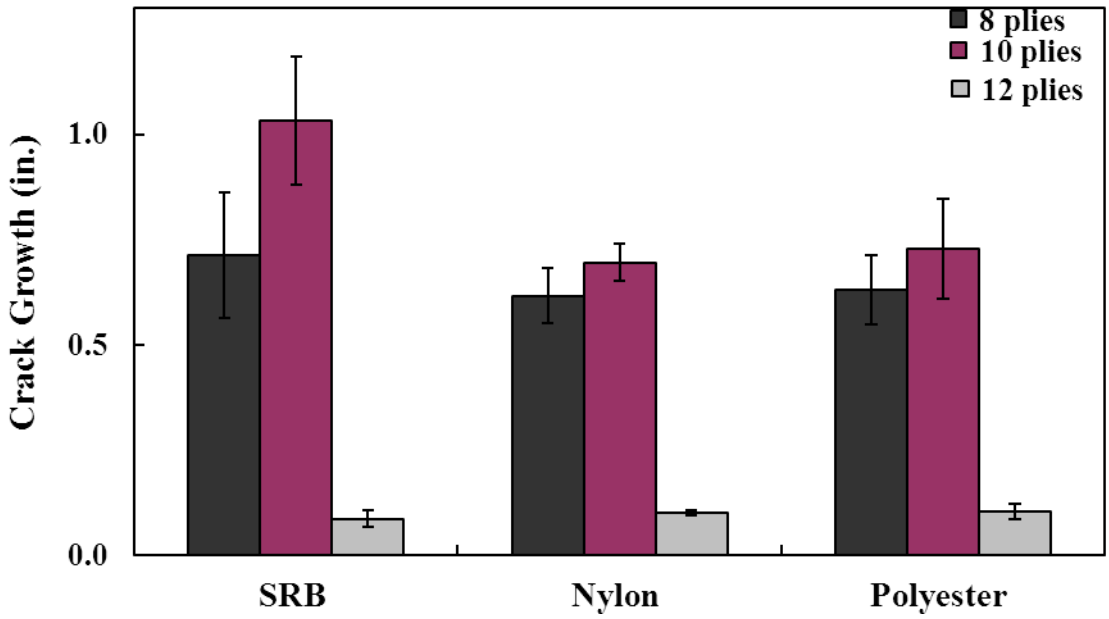


Figure 21. Crack Growth of Composite Wedge Crack Specimen After Immersion in 140°F Water for 24 Hours

3.5 EFFECT OF ABRASIVE SURFACE TREATMENTS.

The poor adhesion observed with some peel ply materials has provided motivation to consider secondary surface treatments. The more common treatments involve sanding or grit blasting. To consider the effects of secondary treatments, composite panels were either grit blasted with 80- or 220-grit garnet or sanded using 220-grit sandpaper. The panels were bonded and machined into standard DCB specimens.

Using polyester peel ply as a control, the average G_{IC} of each treatment is shown in figure 22. The G_{IC} of the sanded surface was slightly higher than the control, while the grit-blasted surfaces were lower. An image of each surface is shown in figure 23. The texture of the polyester peel ply is apparent on its resin-rich surface. The sanding treatment appears to completely remove any evidence of the peel ply, leaving a relatively smooth surface. Both grit-blasted surfaces are relatively rough and show signs of surface erosion. Representative images of the DCB failure surfaces are shown in figure 24. The G_{IC} decreases with increasing adherend failure. Adherend failure, in turn, appears to increase with surface roughness. The pitting from the abrasive techniques may have damaged the fibers and significantly increased the tendency for adherend failure.

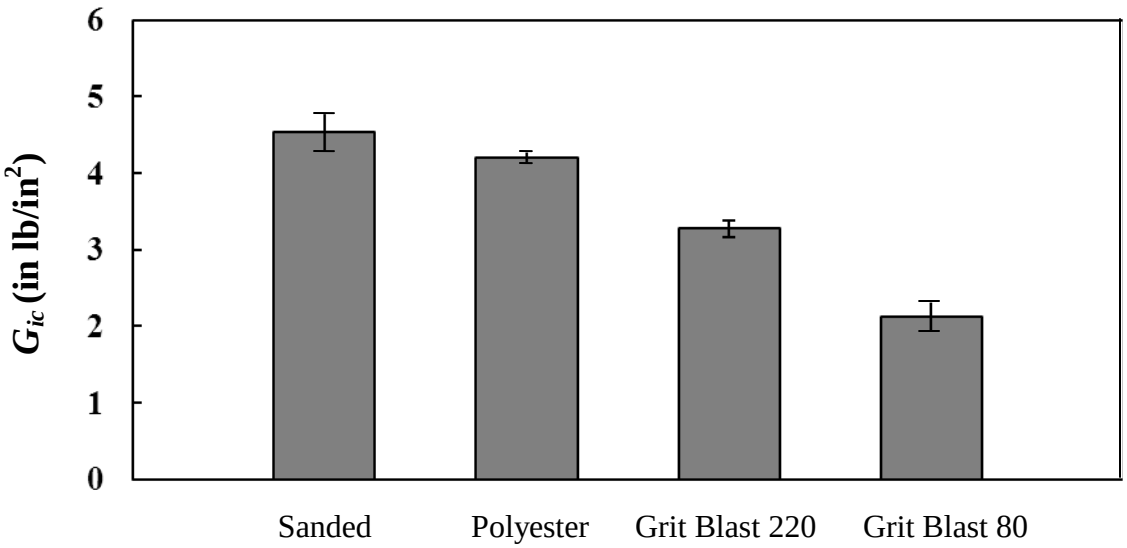


Figure 22. Critical G_{IC} as a Function of Surface Preparation

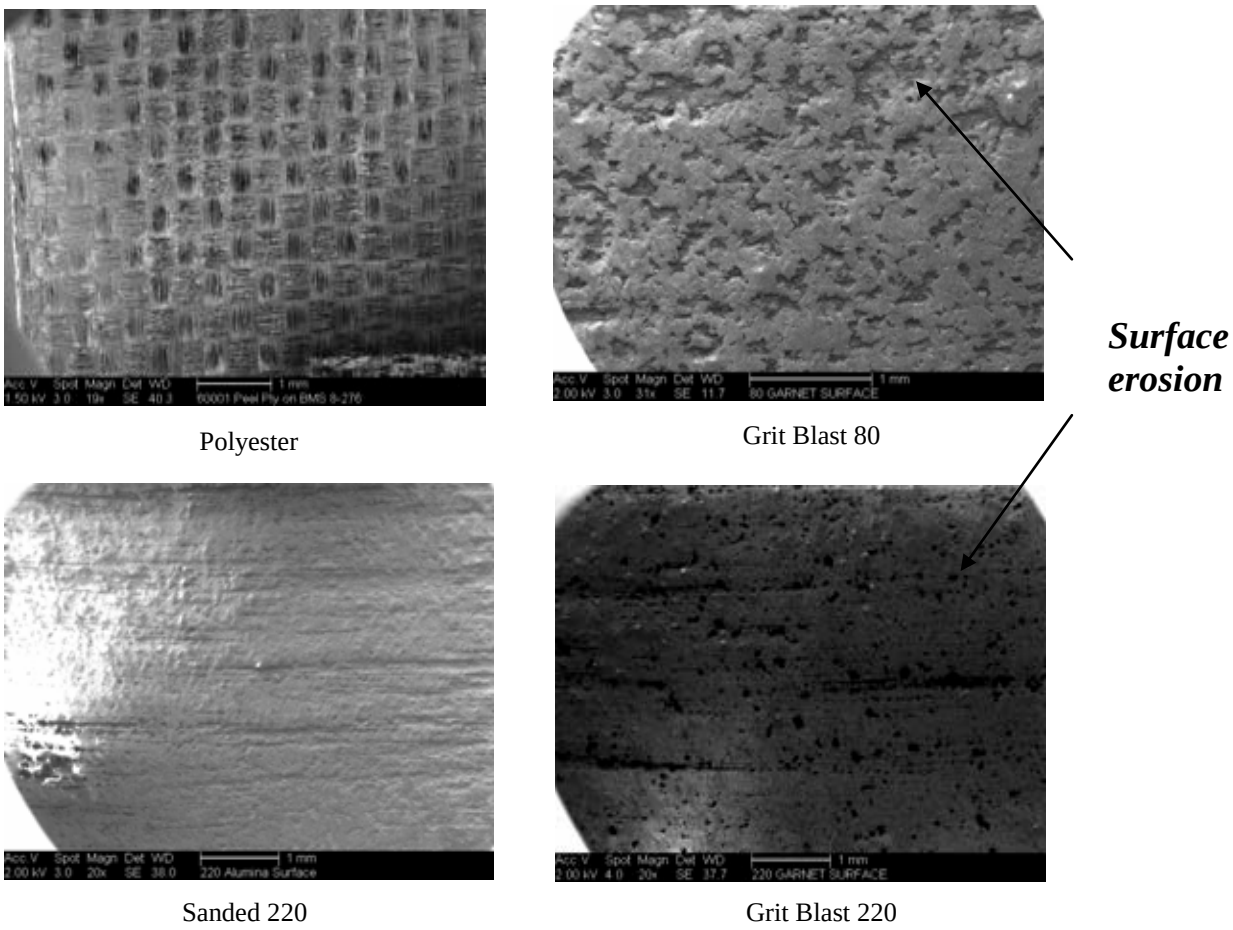
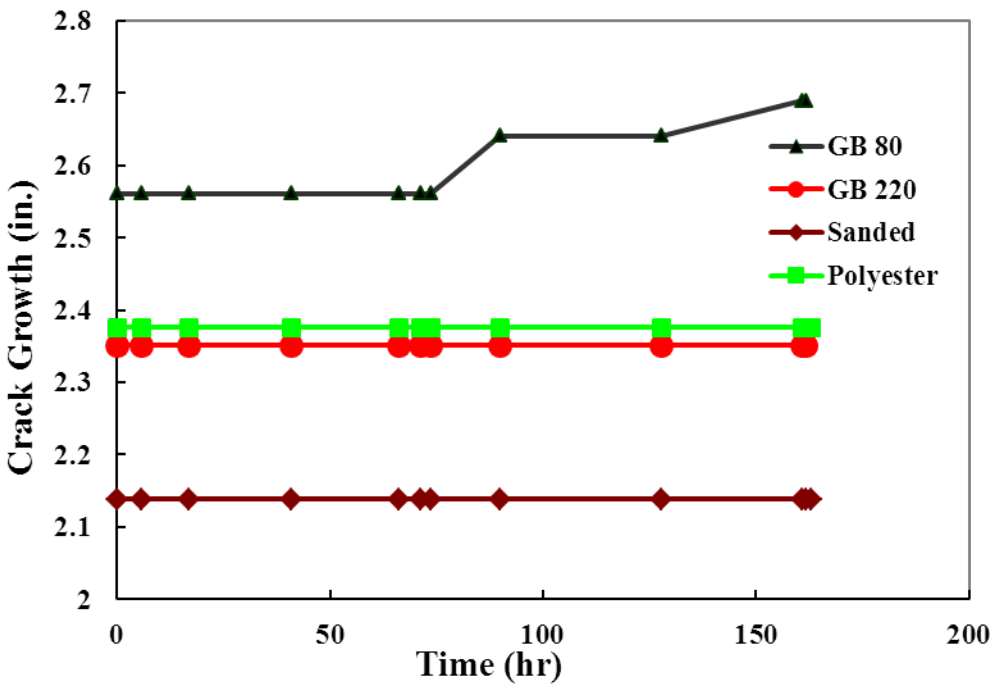


Figure 23. Images of the Polyester Peel Ply and Abrasive Surface Preparations Scanning Electron Microscope

Sanded
99% cohesive, 1% adherend
Polyester
90% cohesive, 10% adherend
Grit Blast 220
70% cohesive, 30% adherend
Grit Blast 80
100% adherend

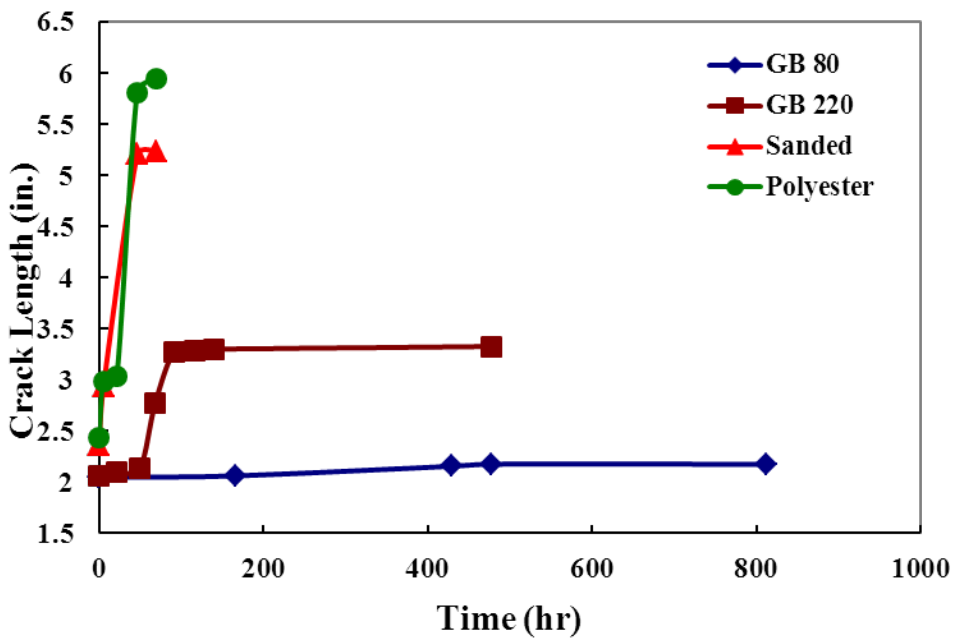
Figure 24. Representative Images of the Failure Modes of DCB Specimens

To determine if load could accelerate the degradation, the DCB specimens were subjected to 90% of their respective baseline crack initiation loads. While immersed in water at 140°F, constant and fluctuating (0.5-Hz) loads of 6.2, 8.4, 9.8, and 10.3 lb were applied on the grit blast 80, grit blast 220, polyester, and sanded DCB specimens, respectively. The mean crack growth of each surface treatment is shown in figures 25 and 26 under constant and fluctuating loads, respectively. The constant load exposure showed little change in crack length, while the fluctuating load showed noticeable crack growth.



GB = Grit blast

Figure 25. Mean Crack Growth of the DCB Specimens Prepared From Abrasive Techniques Under Constant Loading



GB = Grit blast

Figure 26. Mean Crack Growth of the DCB Specimens Prepared From Abrasive Techniques Under Fluctuating Load

Although the grit-blasted surfaces had a lower G_{IC}, they exhibited superior crack growth resistance. This is most likely due to the criterion for selecting the applied load. Failure of the grit-blasted specimens, for instance, continued to be dominated by adherend failure, and the sanded and peel ply surfaces tended to have cohesive failures. Since a weak, but durable, bond is of little practical importance, the tests were repeated using a fluctuating load of constant magnitude (9.5 lb). For this case, the crack growth rate of the grit-blasted specimens was significantly higher than the peel ply or sanded specimens, as shown in figure 27.

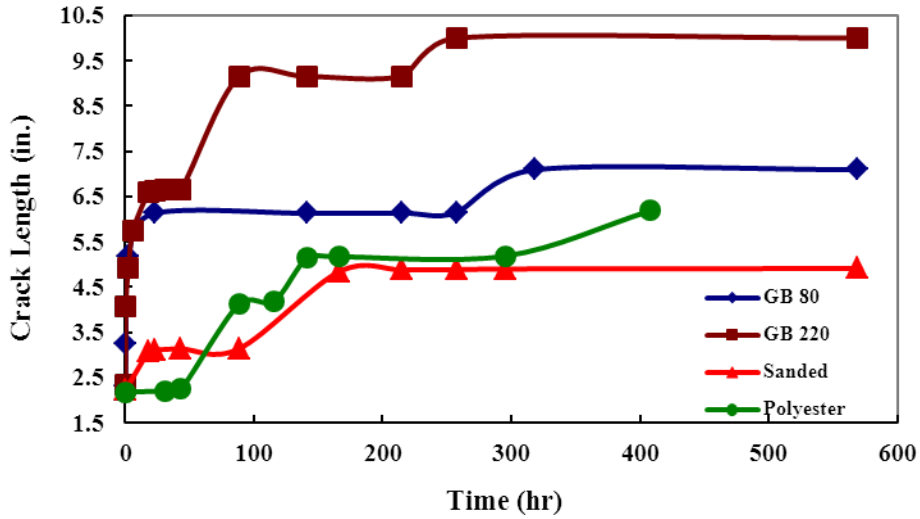


Figure 27. Mean Crack Growth of the DCB Specimens Prepared From Abrasive Techniques Under a Fluctuating Loading of 9.5 lb

Representative failure modes of specimens exposed to repeated loading are shown in figure 28. The failure modes are similar to those found previously, where increased fracture resistance was associated with cohesive failure.

GB 80
100% adherend
GB 220
60% cohesive 40% adherend
Polyester
50% cohesive 50% adherend
Sanded
90% cohesive 10% adherend

Figure 28. Failure Modes of DCB Specimens Exposed to a Fluctuating Load of 9.5 lb

4. CONCLUSIONS.

This study determined the effects of surface preparation on composite adherends and accelerated test methods that may be used to compare their long-term degradation.

BMS 8-276 Form 3 laminates were processed using polyester, nylon, and siloxane-coated polyester peel ply. The effect of secondary abrasion was considered by sanding and grit blasting. All specimens were bonded with AF555 (3M) that was formulated to be moisture resistant during bonding.

The AF555 adhesive was resistant to prebond adherend moisture content; however, the composite adherends tended to fail by interlaminar shear as the moisture content increased. This occurred for both the low-cost and classic material forms. The tendency for adherend failure may have been influenced by a toughening film on the prepreg surface.

Of the surfaces prepared from the three peel plies, polyester provided superior shear strength and fracture toughness with cohesive and interlaminar failure modes. Secondary abrasive operations did little to improve adhesion beyond the polyester peel ply and, in some cases, lowered the bond strength. Sanded surfaces had slightly higher strain energy release rates (G_{IC}) than peel ply, while grit-blasted surfaces had significantly lower G_{IC}. The grit-blasting operation caused surface pitting that may have contributed to the reduced strength.

Combining stress, temperature, and moisture accelerated degradation beyond the effect of these components individually. Temperature accelerated moisture diffusion. The residual shear strength decreased with creep stress. While immersed in water, crack growth in double cantilever beam specimens was accelerated using a fluctuating load.

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